

Going Up A GPS Receiver Adapts to Space

REVIEW DRAFT

When the first GPS receiver in space arrives on the International Space Station in 2001, five years of creative solutions to design and testing challenges will pay off. Here's how a commercial terrestrial GPS receiver got off the shelf and into space.

E. Glenn Lightsey

Center for Space Research,
Department of Aerospace
Engineering and Engineering
Mechanics, University of Texas

On some trips, the journey is just as interesting as the destination. This analogy applies well to the use of GPS on the International Space Station (ISS). From the earliest days of the ISS program, when NASA decided that GPS would be the primary source of time, navigation, and attitude information on the station, it was clear that the development team would need a lot of creativity to create a device that met the station's special requirements. The team has put five years into developing and testing the GPS receiver that will be installed on the space station in 2001. The first flight demonstration of the new receiver in space, during a May 2000 mission, showed that the team successfully met the challenges of adapting a terrestrial receiver for space.

REASONS FOR GPS

The justification for placing a GPS receiver on a spacecraft is fairly clear.

Position Monitoring. Practically all spacecraft require some form of tracking and monitoring from the ground. Many spacecraft can also benefit from information about their own position. For example, if the spacecraft has to execute a maneuver, it must know its current position in orbit. In the past, NASA obtained this information from radar tracking, which included scheduling ground stations, processing the data, issuing an orbit prediction, and uploading an estimate to the spacecraft. By then, the original measurement could be several hours old. A GPS receiver performs this measurement directly,

<<<---Glenn: We'll still use the picture of the ISS, but it will just be the picture on the first page of the article -- it won't have a figure number.

and instantaneously provides the information to the vehicle. The reduction of scheduling, manpower, and data processing requirements streamlines the spacecraft operations and saves mission cost.

Timing. Many spacecraft also have very accurate timing needs. They may need to collect measurements very precisely, or coordinate measurements with other instruments on the ground or on other spacecraft. These requirements for timing accuracy and stability have traditionally necessitated the addition of an expensive clock to the satellite. A GPS receiver on the satellite, however, can steer a much less expensive clock (similar to the quartz oscillator in a watch) by GPS time to provide a very accurate, stable, and standard time system across multiple vehicles.

Attitude Determination. For the past decade, GPS receivers have been able to measure the direction that a vehicle is pointing, also known as its attitude, relative to some reference. The most common method uses more than one GPS antenna and differences the carrier phase measurements to determine the vehicle's attitude, as shown in figure 1. This has been an area of ongoing research for several years, and it is generally accepted that with a separation of a few meters, attitude information can be reliably produced to within 1 degree. A spacecraft using GPS for attitude determination in addition to navigation and timing can eliminate other sensors and hardware used for these purposes and further save mass, power, and cost.

REASONS TO ADAPT

Why not just take a mass-produced civilian receiver and fly it in space? If you can buy a handheld GPS receiver in a retail store for less than \$100, what is so different about using that same technology in space? This often-asked question is understandable — after all, at the space station's relatively low orbital altitude, the technology that works on the ground should work in space (ISS altitude is 280 km, much lower than the GPS constellation altitude of about 20,000 km). There are many reasons, however, why the same receivers that work on the ground do not work in space.

Environmental Stress. From an environmental perspective, operations in space are much more demanding than those on Earth. Electronic devices must withstand launch vibration and greater temperature swings than are usually found on Earth. Equipment in space is exposed to radiation from which Earth's atmosphere would shield it on the

ground. And there is very low risk tolerance, which necessitates the highest quality parts and extensive preflight testing. All these factors drive up unit cost, which for a space receiver ranges widely from tens of thousands of dollars for "as is" avionics-grade receivers to as much as a million dollars for custom designed, radiation-hardened products.

High Travel Velocities. Like hardware, the algorithms and software inside the GPS receiver must also be modified for operation in space. Satellites travel much faster than airplanes — several kilometers per second — and the range of possible Doppler shift of the incoming signal is correspondingly wider in space than on the ground. GPS signal correlators and tracking loops must be redesigned to accommodate these different dynamics. Furthermore, because the receiver's position and velocity change so rapidly in its orbit compared with typical ground operation, the common technique of using a previous known position to "bootstrap" a receiver to lock onto GPS signals after power-on does not work in space. Even a few seconds of data dropout can result in the receiver becoming permanently "lost in space" if the orbital motion of the vehicle is not taken into account. Fortunately, physics can predict the spacecraft's orbit, and so the orbit elements — parameters that describe the orbit — of the vehicle can help estimate the current position and velocity, given time as an input.

Different Geometry. GPS satellites rise and set much faster in the vehicle's reference frame in space. A satellite that is typically visible for more than 5 hours during a ground-based pass may be visible for only 45 minutes in a low Earth orbit for a vehicle such as the Space Station. The receiver designed for space must therefore anticipate which satellites will be the best to track and must react to the changing geometry more nimbly than a ground receiver can.

Attitude Variations. Finally, the range of attitude motion is generally much greater in space. On the ground, most receivers assume that the antennas are zenith pointed (i.e., "up"). Even for an aircraft in a steep 45-degree angle bank, this assumption is still approximately true. In space, a receiver's antenna may be pointed "up" in one part of the orbit and "down" in another part — and go through every angle in a full rotation during the course of the orbit. (This attitude profile, illustrated in figure 2, is called an inertial hold.) A well-designed space receiver must take advantage of any knowledge of the antenna direction and update its

satellite selection to find the most useful GPS signals within its field of view.

Clearly, space operation offers new challenges that make the existing ground receivers unsuitable. It is certainly possible, however, to start with an existing ground receiver, and make selected modifications in software and hardware to enable it to operate in space. This retains some of the desirable features of mass-produced technology (such as parts availability and lower cost) and reduces the scope of the design task, in exchange for accepting some limitations of the original design. Thus there are really two categories of GPS receivers used for space: receivers specifically designed for space, and ground receivers modified to operate in space. In this market environment, the space station project, managed out of NASA's Johnson Space Center, decided to procure a GPS receiver for operation in space.

CREATING A GPS RECEIVER FOR SPACE

By the mid-1990s, a handful of experiments had shown that attitude determination was possible on satellites in low Earth orbit. The Johnson Space Center researchers flew their own experiment on the Space Shuttle Orbiter in 1996 (STS-77), known as GANE (GPS Attitude and Navigation Experiment [figure 3]), that successfully demonstrated an attitude-determination-capable receiver manufactured by a commercial receiver vendor. Engineers at Stanford University and NASA's Goddard Space Flight Center had modified this receiver for space operations. On the basis of the GANE results, NASA pressed forward with its ambitious decision that the space station's GPS receiver should provide position and time as well as attitude. Although the attitude determination concept had been experimentally demonstrated in space, no commercially available receivers could meet these requirements off the shelf.

Responding to Johnson Space Center's Request for Proposal for a GPS-based navigator to support multiple NASA programs, Honeywell Corporation put together the team that would ultimately build Space Station's GPS Receiver. Honeywell assumed the role of prime contractor and systems integrator and based the design on its Embedded GPS/INS (EGI) chassis that is used for other applications.

The Chassis. The EGI chassis provides a vibration-resistant housing for the GPS receiver and for the Inertial Navigation System (INS), power conditioning electron-

Glenn: I took this information from the Simpson paper. Please read it carefully to make sure I haven't reduced anything to gibberish.----->>>

ics, and an RS-422-to-1553 telemetry interface converter. The INS is a laser ring gyro package necessary for sensing accelerations and blending data with GPS solutions to improve accuracy.

Hardware Modifications. The manufacturer of the commercial ground receiver provided the embedded hardware required for the GPS receiver. The basis for the receiver was a 12-channel, C/A code, avionics-grade receiver, modified so that six channels were dedicated to C/A code tracking for navigation. The remaining six were multiplexed across four antenna inputs to provide differential carrier-phase measurements. The manufacturer also added a second microprocessor to handle space operation and attitude determination tasks. Figure 4 shows the receiver.

Software Modifications. Goddard Space Flight Center engineers modified the receiver's source code, adding the following new algorithms and routines to enable it to supply navigation information and determine attitude in space:

Modifications to the receiver tracking loops and position-fixing logic accommodated the greater altitudes, velocities, and accelerations found in space.

An orbit propagator algorithm facilitated initial acquisition and reacquisition of GPS signals.

An antenna boresight vector algorithm compensated for the fact that the antenna array is pitched 41 degrees down.

New reference frames for attitude solution output were added.

New routines allowed calibration-free attitude determination.

A routine to calculate Attitude Dilution of Precision (ADOP) accounted for the antenna array geometry in addition to the GPS lines of sight.

A routine was added to allow the receiver to function on three antennas in the event that one fails.

Modifications made the receiver's attitude determination components and navigation determination components use the same communication protocol.

The paper cited in the Further Reading box gives more information about these algorithms.

Goddard engineers also performed acceptance testing of the GPS before delivering it to Honeywell. The total integrated package of EGI plus space-capable GPS receiver was named the Space Integrated GPS/INS (SIGI) (figure 5).

Redundancy with Other Systems. GPS is not the only source of attitude information on the

ISS. The SIGI combines the GPS attitude measurements in a dynamic filter with measurements from a ring gyro assembly (RGA) to produce an estimate of the ISS's attitude. Also, the Russians have their own attitude determination system on the Russian Service Module, which can provide backup attitude information if necessary.

Two SIGIs will be installed in space. Although the unit on the space station itself will contain an INS, the INS will not be used for inertial navigation, as the station is equipped with more accurate RGA sensors. However, the SIGI that is mounted on the station's emergency reentry vehicle, the Crew Return Vehicle (CRV), will have an INS that will be used for navigation.

TESTING THE RECEIVER

The Signal Simulator. Testing the GPS receiver presented another challenge. Because the receiver was designed to operate in the dynamics of space, it was impossible to use ground-based tests to determine performance. Testing was completed using a commercially available product known as a GPS Signal Simulator. This device takes inputs such as receiver location and attitude, and GPS satellite locations, determines the appropriate GPS signals for those conditions (code phase, carrier phase, and signal levels), and then generates the radio frequency signals as the receiver would expect to see them. The GPS receiver hardware can then be connected to the Signal Simulator and effectively driven into computing position and attitude solutions for the prescribed conditions—in this case, the Space Station's orbit.

The GPS Signal Simulator, shown in figure 6, is an amazing piece of hardware both in its capability and its complexity. The simulator enables engineers to perform certain types of dynamic tests on the receiver in a laboratory environment, exercising both receiver software and hardware functions, that would not otherwise be possible. It was certainly a critical component during the development and testing of the SIGI receiver. However, the simulator is also an incredibly complex device that requires expertise to simply maintain and use properly. Setting up and properly executing the correct test was often just as difficult a job as developing new algorithms for the receiver. The team broke new ground in testing techniques for space receivers during this program.

Because the SIGI receiver will be a critical piece of equipment in the Space Station guidance and control system, it

<<<<-----Is this the RGA in the INS, or an external one? Need to reword this to clarify one way or the other.

endured several hundred hours of official testing on the GPS Signal Simulator, simulating all different types of initial conditions and failure scenarios. It also underwent hundreds of hours more of unofficial testing, making this probably one of the most thoroughly tested receivers in history. Test results guided the receiver's development program and also demonstrated that it should meet all of its performance requirements for the Station.

Testing in Flight. Although simulator testing is the best way to reproduce the dynamics of satellites in a lab, it is still not as good as the real thing. So it was necessary to fly the SIGI receiver in space to determine if it would perform consistently with what had been predicted by ground testing. The first flight demonstration of SIGI in space took place in May 2000 on the Space Shuttle Orbiter (STS-101) (figure 7) under the name SIGI Operational Attitude Readiness (SOAR). In the SOAR experiment, an antenna array geometrically identical to the one that will be used on Space Station was flown in the Orbiter cargo bay. The receiver collected data with the Orbiter in attitudes similar to that of the space station. It also collected data when the Orbiter was actually docked to the Station and its view of the GPS satellites was obscured. The obscured visibility cases are important because the receiver will experience these situations when other vehicles (such as the Space Shuttle) are docked with or are near the Station. On this flight, two separate star trackers provided a truth reference for the GPS attitude solutions.

The SOAR data was still being analyzed as this article was going to press, but all of the objectives were met. For example, GPS position accuracy was well within specification, and GPS attitude accuracy was within acceptable limits (generally less than 1 degree per axis). In general, the SIGI receiver met all of the requirements for the space station, clearing the way for the receiver to be installed on the station within the next year.

A second SOAR flight in September 2000 will provide additional on-orbit SIGI performance data both for the space station and for the station's emergency reentry vehicle, known as the Crew Return Vehicle (CRV). The CRV, shown in figure 8, will utilize both the GPS and INS capabilities provided by the SIGI navigation unit. This vehicle, scheduled to become an operational part of the station in 2004 or 2005, has some challenging additional requirements for its guidance system, given the more complex

application of the SIGI. This includes timely separation from the Space Station and support for flying the CRV from orbital attitudes to safe landing on the ground. The SOAR 2 mission, along with a number of entry flight tests, will help define what is technically feasible with the current SIGI receiver design to ensure a robust and safe CRV design.

A LONG-AWAITED GPS APPLICATION

Current plans for the space station call for the GPS receiver to be installed on the U.S. lab module of the station in early 2001 (ISS Assembly Flight 5A), followed by the attachment of the antenna array in late 2001 (Flight 8A). At that point the U.S. ISS guidance and control system will be operational.

The flight of SIGI on the space station represents a "coming of age" for GPS technology on spacecraft. For at least a decade, the promise of using GPS receivers to automate spacecraft operations, simplify satellite design, and reduce mission costs has enticed satellite designers. Integration of this technology onto spacecraft has been slower than some originally anticipated. However, given the complexity of the GPS sensor, and the importance of the functions it performs, its incorporation into mainstream satellite design has probably occurred at a very reasonable pace. Going from providing experimental payloads on small, unmanned satellites to performing critical operational functions on manned vehicles has been a major evolution. If all goes as planned in the next few months, GPS receivers will soon provide those critical functions on one of the most complex spacecraft in history, the International Space Station.

This application . . .

revealed

- the conditions of space make ground receivers unsuitable for use in space
- a terrestrial receiver was modified for space operation
- in-flight testing confirmed that the receiver will meet the space station's needs

Glenn: City and state for GSSI? Is GPS Signal Simulations the correct name? There's a company called Global Simulation Systems that goes by GSSI, too.----->>>>>>>>

MANUFACTURERS

Trimble Navigation (Sunnyvale, California) makes the Force-19 GPS receiver that was the basis for the SIGI receiver. The GPS Signal Simulator is made by **GPS Signal Simulations, Inc. (GSSI)**

FURTHER READING

"Design and Performance of Space Algorithms for the GPS Receiver used on International Space Station and Crew Return Vehicle," by E. Glenn Lightsey et al.,

FIGURE CAPTIONS

Figure 1. The principles of carrier phase attitude determination. If the user knows the line of sight and the carrier phase at each antenna for several GPS measurements, the separation vector between the two antennas, and thus the attitude of the vehicle, can be solved.

Figure 2. A satellite in an inertial hold pointing mode. Notice that the antennas that are facing the GPS satellites at one point in the orbit are facing the earth half an orbit later.

Figure 3. The GANE experiment hardware at integration. The four GPS antennas are at the corners of the rectangular structure, indicated by choke rings.

Figure 4. The GPS receiver, packaged for housing in the EGL chassis.

Figure 5. The complete SIGI box, which will be housed in the US Lab Module on the space station.

Figure 6. The GPS laboratory test facility at Goddard Space Flight Test Center. The GPS Signal Simulator is mounted in the rack at the middle of the picture.

Figure 7. The International Space Station in May 2000, as photographed from Orbiter Atlantis on STS-101. The SOAR experiment resided in the Orbiter bay during this mission. Attitude solutions were computed throughout the 10-day mission, including the docked phase.

Figure 8. A model of the Crew Return Vehicle attached to the wing of a NASA aircraft during an atmospheric drop test. The Crew Return Vehicle will be used for emergency egress from the space station after 2005.